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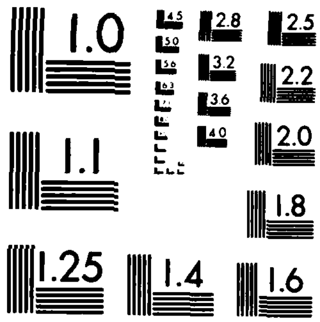

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DNA-TR-83-13

ANALYSIS OF RADIATION EXPOSURE FOR NAVAL PERSONNEL AT OPERATION SANDSTONE

Science Applications International Corporation
P.O. Box 1303
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15 August 1983

Technical Report

CONTRACT No. DNA 001-83-C-0039

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1. REPORT NUMBER DNA-TR-83-13	2. GOVT ACCESSION NO. AD-A152 188	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYSIS OF RADIATION EXPOSURE FOR NAVAL PERSONNEL AT OPERATION SANDSTONE		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER SAI-83/1055
7. AUTHOR(s) C. Thomas J. Goetz J. Stuart J. Klemm		8. CONTRACT OR GRANT NUMBER(s) DNA 001-83-C-0039
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications International Corporation PO Box 1303 McLean, VA 22101-1303		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task Q25QMXMK-00001
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D.C. 20305-1000		12. REPORT DATE 15 August 1983
		13. NUMBER OF PAGES 50
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A since UNCLASSIFIED

16. DISTRIBUTION STATEMENT (of this Report)

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18. SUPPLEMENTARY NOTES

This work was sponsored by the Defense Nuclear Agency under RDT&E RMSS Code X350083469 Q25QMXMK00001 H2590D.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Operation SANDSTONE
Radiation Exposure Assessment
Nuclear Test Personnel Review (NTPR)
Joint Task Force Seven
Task Group 7.3
Oceanic Nuclear Tests
Ship Shielding

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Radiation environments are reconstructed for Task Group 7.3 ships and the residence islands of Enewetak and Kwajalein Atolls resulting from the three nuclear detonations comprising Operation SANDSTONE (April-May 1948). Secondary (late-time) fallout was the source of virtually all of the radioactive contamination on the ships and islands, most of which resulted from Shots X-RAY and YOKE. Fallout from Shot ZEBRA was minimal. From the reconstructed free-field radiological environments, an equivalent personnel film

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20. ABSTRACT (Continued)

badge dose is calculated and compared to actual dosimetry data obtained during the operation. Calculated doses and dosimetry are consistent, although most of the calculated and film badge doses are below film badge threshold.

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Section 1

INTRODUCTION

Operation SANDSTONE was the second nuclear test series held in the Marshall Islands. It consisted of three nuclear weapon tests at Enewetak* Atoll in the spring of 1948. Operation SANDSTONE was primarily an Atomic Energy Commission (AEC) scientific test series with the armed forces serving in a supporting role.

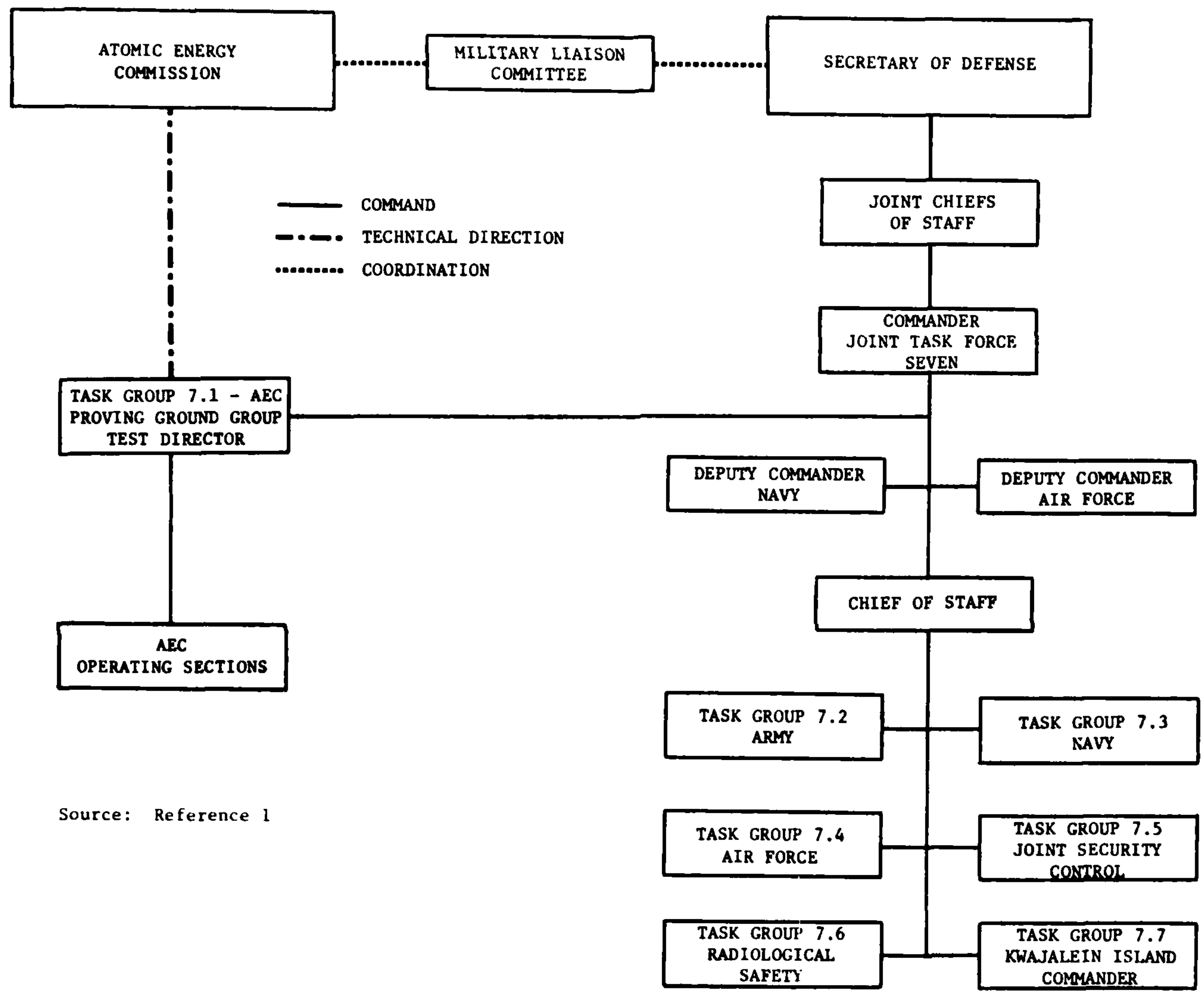
The operation was conducted by a joint military and civilian organization, designated Joint Task Force Seven (JTF 7). This was a military organization in form, but contained military, civil service, and contractor personnel of the Department of Defense and the AEC. The commander of JTF 7 was the appointed representative of the AEC and reported directly to the Joint Chiefs of Staff. The organization of JTF7 is depicted in Figure 1-1. Of over 10,000 people assigned to the task force, approximately 7,000 were attached to the Naval element--Task Group 7.3.

Generally, most of the TG 7.3 personnel remained clear of radiological areas, which were well defined. However, radioactivity from secondary (late-time) fallout did result in widespread, but low-level exposure. Radiation dose to participants is reconstructed from radiological data, ship logs, and crew activity scenarios and compared with the available dosimetry data. The results are portrayed for the crews of 31 vessels that supported the operation and for the island-based personnel on Enewetak Atoll. Because some of the task group personnel were at Kwajalein Atoll during periods of fallout, the radiation environment on Kwajalein is also reconstructed.

1.1 BACKGROUND

Operation SANDSTONE was conducted primarily to proof-test new weapon designs. The Department of Defense participation centered primarily around effects

*Formerly Eniwetok.



Source: Reference 1

Figure 1-1. Joint Task Force Seven Organization

experiments and support to the AEC weapon effects experiments. Enewetak Atoll was selected because it was large enough for the three shots, and because the trade winds would carry fallout from the shots over the open ocean to the north and west (Reference 1). Figure 1-2 shows the main features of Enewetak Atoll and the Operation SANDSTONE shot locations.

The succession of shots was from Enjebi, on the northern edge of the atoll, toward the southeast, to Runit. Winds at Enewetak are usually such that moving the shot points progressively from northwest to southeast minimized the possibility of personnel working in areas contaminated by prior shots. Shot data is shown in Table 1-1.

Table 1-1. Operation SANDSTONE Shot Data

	X-RAY	YOKE	ZEBRA
Date (1948)	15 April	1 May	15 May
Time (local)*	0617	0609	0604
Island (Site)	Enjebi (Janet)	Aomon (Sally)	Runit (Yvonne)
Height of Burst	200 ft.	200 ft.	200 ft.
Yield	37 KT	49 KT	18 KT

*Local time was 12 hours behind GMT. Source: Reference 2.

Before each shot, a weather watch was maintained to ensure that the days selected for the tests would have favorable weather. Wind direction and velocity at all relevant altitudes were critical to minimize the possibility of fallout from the radioactive cloud on task force ships and any inhabited islands. Light, variable winds, which made forecasting more difficult, and winds with a northerly component presented unfavorable conditions for firing. Clouds that would interfere with the visual direction of drone aircraft also made firing conditions unfavorable. Additionally, heavy cloud cover would interfere with aerial photography, but since this was not essential to scientific recording, this condition could be tolerated if other criteria

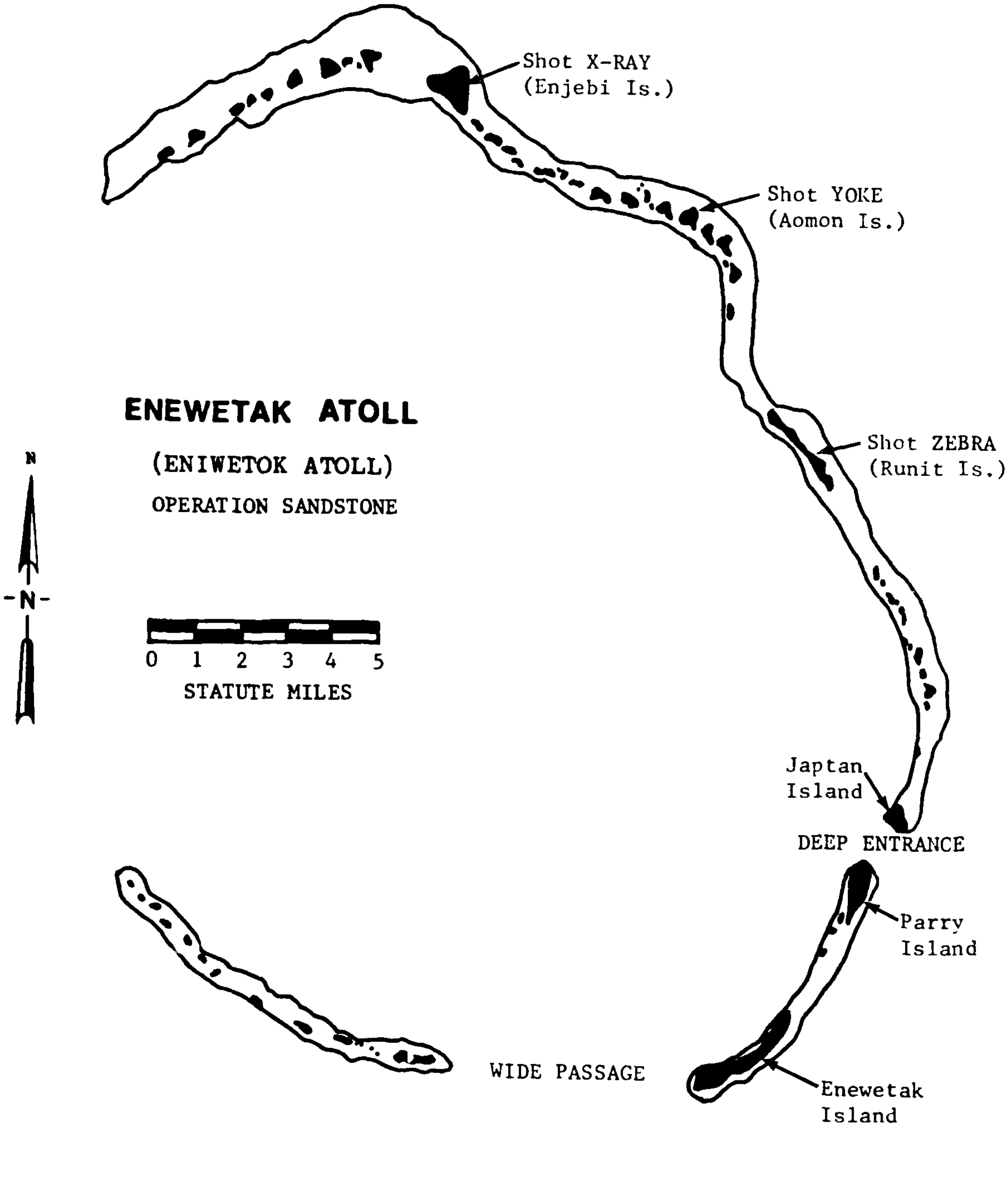


Figure 1-2. Operation SANDSTONE Shot Locations

were favorable. Rainshowers that could be predicted as few and scattered were acceptable, but predicted heavy showers were not acceptable because of possible inte erence with surface photography, which was essential to the scientific effort (Reference 1).

1.2 NAVAL TASK GROUP ORGANIZATION

The Navy task group (TG 7.3) provided support at Enewetak Atoll for the scientific programs and carried out surface and air operations in and around the atoll. The main tasks were to:

- Deliver nuclear components to Enewetak Atoll
- Provide mobile facilities for devices at the test site
- Conduct surface and air security operations
- Provide intra-atoll water transportation
- Plan for evacuation of all personnel from the atoll
- Transport personnel and scientific and naval equipment to and from the atoll
- Provide living accommodations for task group personnel
- Lay cable
- Provide offshore patrols.

In order to carry out these tasks, TG 7.3 was organized into seven functional task units as shown in Table 1-2. The USS MT McKINLEY (AGC-7) was used as the command ship and also had the Weather Center and Air Operations Office on board. The USS CURTISS (AV-4) was a specially modified seaplane tender and was used to transport the nuclear devices to the test area. The USS ALBEMARLE (AV-5) was modified to be the laboratory ship for TG 7.1 and the USS BAIROKO (CVE-115) was used by the radsafe personnel (TG 7.6). The USS COMSTOCK (LSD-19) was the mother ship for the boat pool, which provided water transportation for all task units during the operation. The USS GARDINERS BAY (AVP-39) and eight destroyers provided for continuous surveillance in the ocean areas around Enewetak Atoll.

Table 1-2. TG 7.3 (Navy) Organization and Personnel Summary

Unit/Ship		Personnel
TU 7.3.1	FLAGSHIP UNIT	
	USS MT McKINLEY (AGC-7)	579
TU 7.3.2	MAIN NAVAL TEST UNIT	
	USS CURTISS (AV-4)	559
	USS ALBEMARLE (AV-5)	534
	USS PICKAWAY (APA-222)	292
	USS WARRICK (AKA-89)	194
	USS YANCEY (AKA-93)	155
	USS LST-45	71
	* USS LST-219	60
	* USS LST-611	53
	** USATS FS-211	26
	** USATS FS-370	26
TU 7.3.3	OFF-SHORE PATROL	
	USS GARDINERS BAY (AVP-39)	298
	*** FLEET ACFT SVC SQ 119 (FASRON-119)	33
	*** MEDIUM SEAPLANE PATROL SQ 6 (VP-MS-6)	290
	ESCORT DIVISION 1	
	USS GEORGE (DE-697) (includes COMCORTDIV 1)	148
	USS CURRIER (DE-700)	136
	USS MARSH (DE-699)	139
	USS RABY (DE-698)	145
	USS SPANGLER (DE-696)	136
	DESTROYER DIVISION 52	
	USS HENRY W. TUCKER (DDR-875) (includes COMDESDIV 52)	238
	USS ROGERS (DDR-876)	234
	USS PERKINS (DDR-877)	227
	MISCELLANEOUS	
	*** AVR C-26638	6
	*** AVR C-26653	6
	AIR DEVELOPMENT SQ 4 (VX-4) (on KWAJALEIN)	54
	SONOBUOY MONITOR UNIT (on ENEWETAK)	8

Table 1-2 (Continued)

TU 7.3.4	HELICOPTER UNIT	
	USS BAIROKO (CVE-115)	724
	*** HELICOPTER UNITS	
TU 7.3.5	SERVICE UNIT	
	USS PASIG (AW-3)	227
	USS AREQUIPA (AF-31)	77
	USS MISPILLION (AO-105)	176
	YW-94	11
	YOG-64	11
TU 7.3.6	CABLE UNIT	
	LSM-250	60
	LSM-378	43
	NAVY SIGNAL UNIT #1 (on ENEWETAK)	51
TU 7.3.7	BOAT POOL	
	USS COMSTOCK (LSD-19)	255
	** BOAT POOL	184
	USS ASKARI (ARL-30)	176
	LCI (L)-549	18
	LCI (L)-1054	22
	LCI (L)-1090	21
	*** LCTs 472, 494, 1194, 1345	--
CTG 7.3	* USS DAVISON (DMS-37)	170
	* USS GULL (AMS-16)	24
	* USS PELICAN (AMS-32)	26
	* USS QUICK (DMS-32)	167
	* USS SWALLOW (AMS-36)	23
	Total	7113

* These units received no radioactive contamination at Operation SANDSTONE and are not included in the dose reconstruction effort.

** Army ships attached to TG 7.3.

*** Movements of these smaller units cannot be followed in sufficient detail to permit a dose reconstruction.

Source: Reference 3.

Most of the TG 7.3 personnel consisted of crews aboard the more than 30 ships operating in the Enewetak area. Some naval units such as the Sonobuoy Monitor Unit and Navy Signal Unit #1 lived on Enewetak Island during the entire operation. Further, naval air units operated out of both Enewetak and Kwajalein in support of the test operation.

1.3 METHODOLOGY

The procedures developed in previous dose reconstruction efforts (References 4, 5 and 6) have been adapted to the shipboard and island radiological environments of Operation SANDSTONE. Figure 1-3 depicts the steps taken in calculating personnel doses. These steps are pursued to a level of detail governed by the availability of data. On only a few ships and islands were sufficient data recorded that are currently available for determination of the radiation environment. On most ships, virtually no radiological data exist; their environments are estimated based on their positions, i.e., proximity to other ships and islands with known environments, and their activities when fallout was encountered. Much of the radiological data was obtained from Reference 7. Individual ship deck logs are taken to be the authoritative source of ship position and activity.

Radiological data are used to reconstruct the time-dependent radiation environment on each of the thirty-one ships and on the residence islands of Enewetak and Kwajalein Atolls. Characterization of the radiation environment starts with the determination of free-field intensities from limited radiation intensity data. The periodic radiological surveys, in conjunction with fallout time-of-arrival data, serve to define the free-field intensity as a function of time. For interpolation between readings and for extrapolation beyond the last reading, the intensity is assumed to be a power law function of time after burst, determined from fallout decay rates. Ship-specific data regarding the development of intensity curves for the thirty-one ships are presented in Section 2.

The analysis of radiation exposure to the crew also requires estimation of radiation intensities below deck and the apportionment of crew activities with time

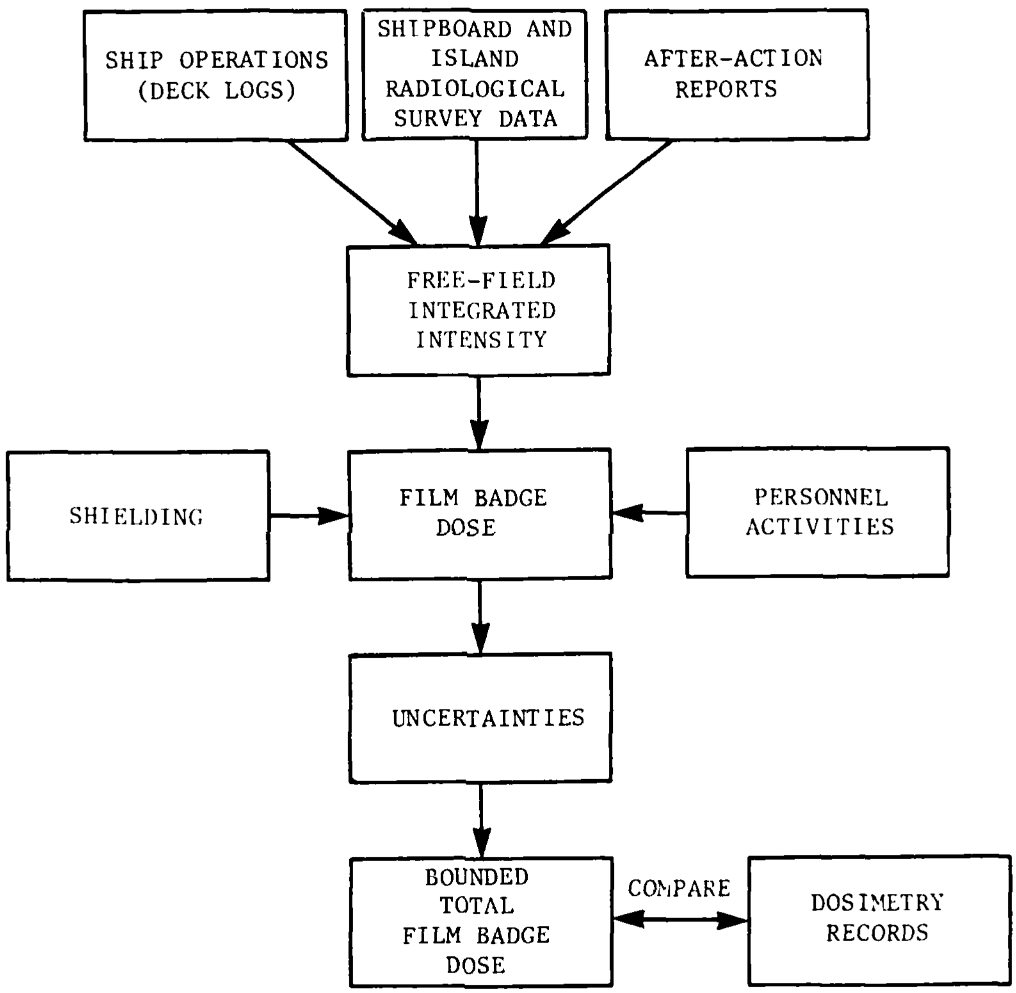


Figure 1-3. Operation SANDSTONE Dose Reconstruction Methodology

below and on deck. A ship-shielding factor is defined as the ratio of intensity below to the mean intensity topside. This factor is approximately 0.1 (Section 2.4) and is nearly constant over the usual crew locations within a ship. Thus, the radiation dose to the crew is dominated by the topside exposure. On-deck intervals are taken to be 0800-1200, 1330-1700, and 1800-2000 hours, which amounts to 40 percent of a day. To facilitate the calculation for shipboard personnel, the daily fractional topside duration, rather than the specified intervals, is used. Because the specified intervals are nearly centered around midday, this approximation is suitable. Similar calculations are performed for island-based personnel to account for the shielding provided by buildings. Both are described in Section 3.

The mean film badge dose to personnel is obtained from time integration of intensity for all intervals below or inside (including the shielding factor) and on deck or outside. A conversion factor of 0.7 is used to account for body shielding in determining the film badge equivalent dose (Reference 8). Total film badge doses are calculated and presented in Section 3. Calculations are continued through 31 May when the roll-up phase of the operation was nearly complete; dose accrual after 31 May is less than 1 mrem per day. An uncertainty analysis of the dose calculations is provided in Section 4. In Section 5, the available dosimetry records are analyzed, and their comparability to the calculated doses is assessed. Conclusions are presented in Section 6.

Section 2

SHIP OPERATIONS AND RADIATION ENVIRONMENTS

This section describes the movements of the TG 7.3 ships while at Enewetak Atoll during Operation SANDSTONE and a broad picture of the radiological environment following the three detonations in the test series. Shipboard radiation environments resulting from radioactive fallout are reconstructed based on available shipboard data. In the absence of ship-specific radiological data, island data from Enewetak and Kwajalein Atolls have been used as appropriate to aid in the reconstruction effort. Possibly because significant fallout was not apparent from any of the SANDSTONE detonations, many of the shipboard measurements taken during the operation were either not documented or, if they were, the reports have not been located. Although the data are sparse, the radiation environments presented in this section adequately reflect the radiation exposure of TG 7.3 personnel during Operation SANDSTONE.

2.1 SHIP OPERATIONS

Of the 31 task group ships at Enewetak during Operation SANDSTONE, only five remained anchored in the lagoon for all three detonations. These were the ALBEMARLE, BAIROKO, CURTISS, MT McKINLEY, and SPANGLER. With the exception of the SPANGLER, which provided anti-submarine warfare (ASW) patrols outside of the lagoon between shots, these ships remained in the lagoon during the entire operation. For several weeks prior to Shot X-RAY and two-week periods before Shots YOKE and ZEBRA, the ALBEMARLE, BAIROKO, CURTISS, and MT McKINLEY were anchored in the northern anchorage area off the respective shot islands, providing personnel and logistical support for the pre-shot activities. The day before each shot, they proceeded to their assigned anchorages off Parry Island in the southern part of the lagoon, where the crews observed the detonations (see Figure 2-1). Shortly after Shots X-RAY and YOKE, these ships returned to the northern anchorage area to prepare for the next detonation. After Shot ZEBRA, the ALBEMARLE, BAIROKO, CURTISS, and MT McKINLEY shifted berths to an area off Enewetak Island and, on 21 May, departed Enewetak for Pearl Harbor in company with the PERKINS, RABY, SPANGLER, and TUCKER, which provided screen for the convoy.

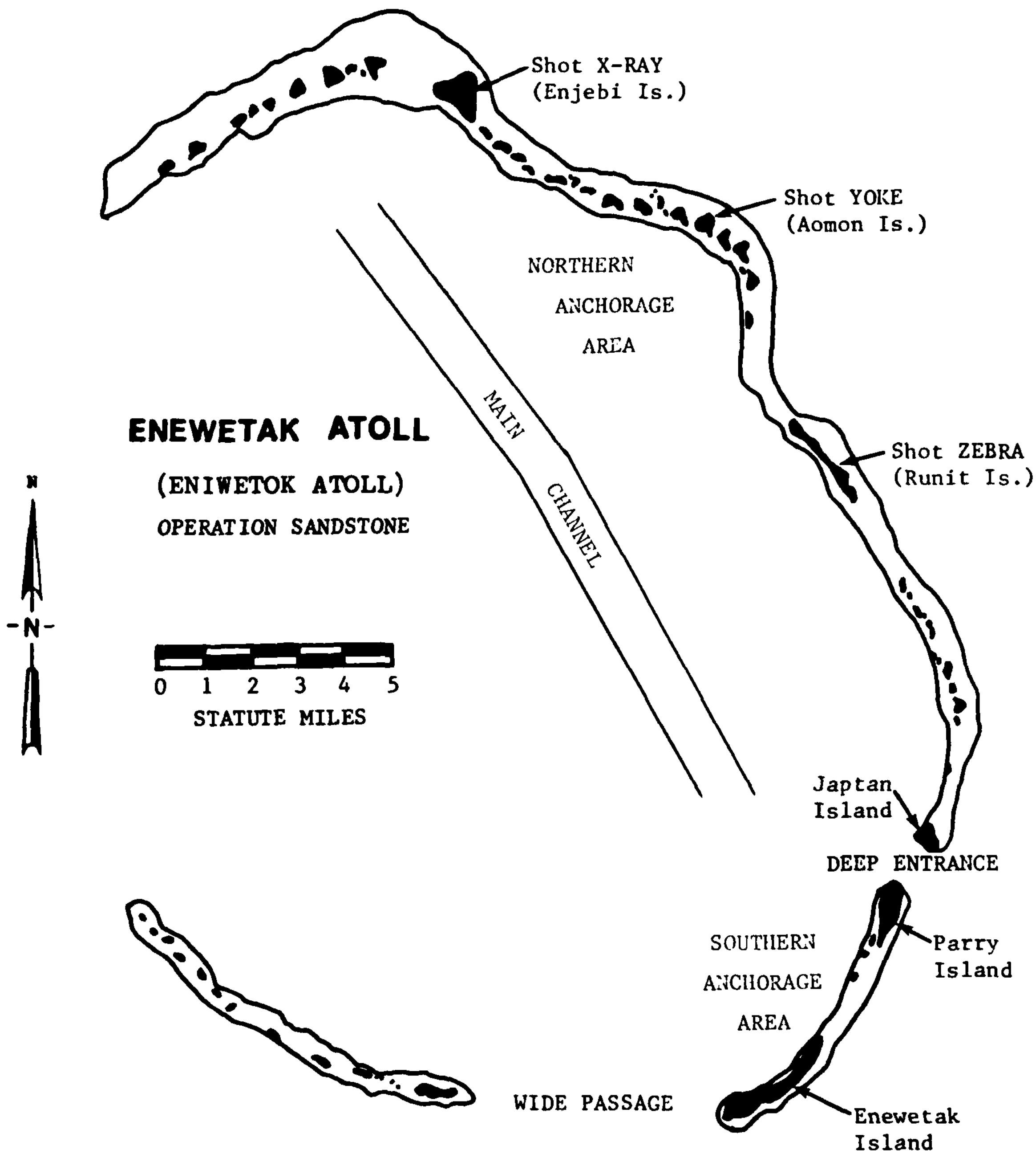


Figure 2-1. Enewetak Atoll Anchorage Areas

The other 26 task group ships evacuated the lagoon the day before each shot and returned to the lagoon several hours after the detonations. While outside of the lagoon, these ships were assigned to one of two task units formed for the pre-shot evacuations--TU 7.3.5 and TU 7.3.8. Of 12 vessels assigned to TU 7.3.5 (excluding the destroyer escort), only nine were at Enewetak for all three shots. These were the ASKARI, PASIG, LSM-250, LST-45, LCI-1054, LCI-1090, YW-94, YOG-64, and AFS-370. Generally all nine of these vessels followed similar routines before and after each shot. They evacuated* the lagoon the day before the test to an area a minimum of 17 miles south or southeast of the shot island. While outside of the lagoon, the MARSH was assigned to TU 7.3.5 to provide ASW screen. Several hours after the detonation, the ships returned to the southern anchorage area off Enewetak and Parry Islands. (One exception to this was the LST-45, which anchored in the northern anchorage area upon returning to the lagoon). In the two-week periods between shots, some of these ships (the LCI-1054, LCI-1090, YW-94 and YOG-64) provided transportation and services (fuel, oil, and water) for those in the northern anchorage area, but all remained in the confines of the lagoon. The three other ships assigned to TU 7.3.5 were the AREQUIPA, LSM-378 and AFS-211. The AREQUIPA participated only at Shot X-RAY and departed the lagoon on 20 April, for Pearl Harbor. The AFS-211 participated only at Shot YOKE and was at Bikini and Mili Atolls for Shots X-RAY and ZEBRA, respectively. It departed Mili on 16 May and arrived at Kwajalein on 17 May. LSM-378 departed Kwajalein during the evening of 14 April and arrived at Enewetak on 16 April; hence, it participated only at Shots YOKE and ZEBRA.

After Shot ZEBRA, the PASIG, after taking a brief trip to Bikini and Kwajalein, departed Enewetak on 24 May in company with the LCI-1054 and LCI-1090 enroute to Pearl Harbor. The LST-45, LSM-250, and LSM-378 also departed for Pearl Harbor on the same day. On 29 May, the ASKARI departed for Kwajalein in company with YOG-64 and YW-94. It is not known how long after Shot ZEBRA that the AFS-370 departed Enewetak.

*YOG-64 remained in the lagoon for Shot YOKE, but its crew was evacuated to the ASKARI.

The five ships assigned to TU 7.3.8 (excluding the destroyer escort) were the COMSTOCK, GARDINERS BAY, MISPILLION, PICKAWAY, and WARRICK. Personnel on these vessels observed the detonations from positions a minimum of 15 miles southeast of each shot. While the task unit was outside of the lagoon, the CURRIER was assigned to provide ASW screen, returning to its off-shore patrol duties shortly after each shot. Except for the pre-shot evacuations, a brief trip to Guam on 5-12 May by the MISPILLION, departure for Kwajalein on 9 May for the WARRICK, and brief sorties out of the lagoon by the PICKAWAY, these ships remained in the lagoon for the entire operation. After Shot ZEBRA, the MISPILLION, COMSTOCK and PICKAWAY departed Enewetak enroute to Kwajalein on 21, 26, and 27 May, respectively. The COMSTOCK returned to Enewetak for 3 days on 28 May and, on 31 May, departed for Pearl Harbor. The GARDINERS BAY departed on 22 May, also bound for Pearl Harbor.

Another ship that evacuated the lagoon for each shot, the LCI-549, was not asssigned to either of the two main task units formed for the evacuation. Instead, it acted independently as a drone reference vessel and maintained a position just off Wide Passage (see Figure 2-1) for each detonation. After each shot, it returned to the lagoon and was used as part of the boat pool. After Shot ZEBRA, the LCI-549 departed Enewetak on 24 May in company with the PASIG, LCI-1054, and LCI-1090, all bound for Pearl Harbor.

Another ship that participated at Enewetak during Operation SANDSTONE was the YANCEY. It departed Pearl Harbor sometime after Shot YOKE and did not arrive at Enewetak until 16 May, one day after Shot ZEBRA. It unloaded cargo for approximately 10 days and, on 26 May, departed Enewetak for Oakland, California.

There were eight destroyers (DEs and DDRs) assigned to TU 7.3.3 that supported ship movements to and from Enewetak Atoll and also provided continuous ASW patrols around the atoll while the operation was in progess. At shot times, the MARSH and CURRIER provided ASW screens for TU 7.3.5, and TU 7.3.8, respectively, while the SPANGLER provided screen for the ships that remained in the lagoon. The remaining destroyers, the GEORGE, PERKINS, RABY, ROGERS, and TUCKER, were on patrol in

their assigned sectors around Enewetak Atoll. Figure 2-2 depicts the destroyer patrol sector chart for Operation SANDSTONE. When used in conjunction with Table 2-1, the movements of all of the destroyers can be detailed from 15 April to 15 May 1948. When the destroyers were not on patrol, they remained anchored in the lagoon, where they took on fuel, oil, and water in preparation for their next patrol assignment. From Figure 2-2 and Table 2-1, it is noted that the immediate ocean area surrounding the atoll (Sectors ABLE, BAKER, and CHARLIE) was under constant surveillance by the offshore patrol unit. In addition, both major entrances to the lagoon (Wide Passage and Deep Entrance) were also under constant patrol. The outer patrol sectors (Sectors DOG, EASY, and FOX) were usually patrolled several days before and after each detonation.

With the exception of the RABY, which took a brief trip to Bikini on 1-3 May, all of the destroyers remained in the immediate vicinity of Enewetak for the entire operation. After the operation, the ROGERS departed the lagoon on 20 May for Rongerik Atoll. On 21 May, the PERKINS, RABY, SPANGLER, and TUCKER departed Enewetak and provided screen for the ALBEMARLE, BAIROKO, CURTISS, and MT McKINLEY while enroute to Pearl Harbor. The CURRIER and GEORGE departed the lagoon on 25 May for Pearl Harbor, while the MARSH did not leave for Pearl Harbor until 3 June.

Table 2-2 is a summary of the ships participating at Operation SANDSTONE. It should be noted that many of the ships were assigned to task units for the pre-shot evacuations other than the units they were assigned to in the TG 7.3 organization (See Table 1-2).

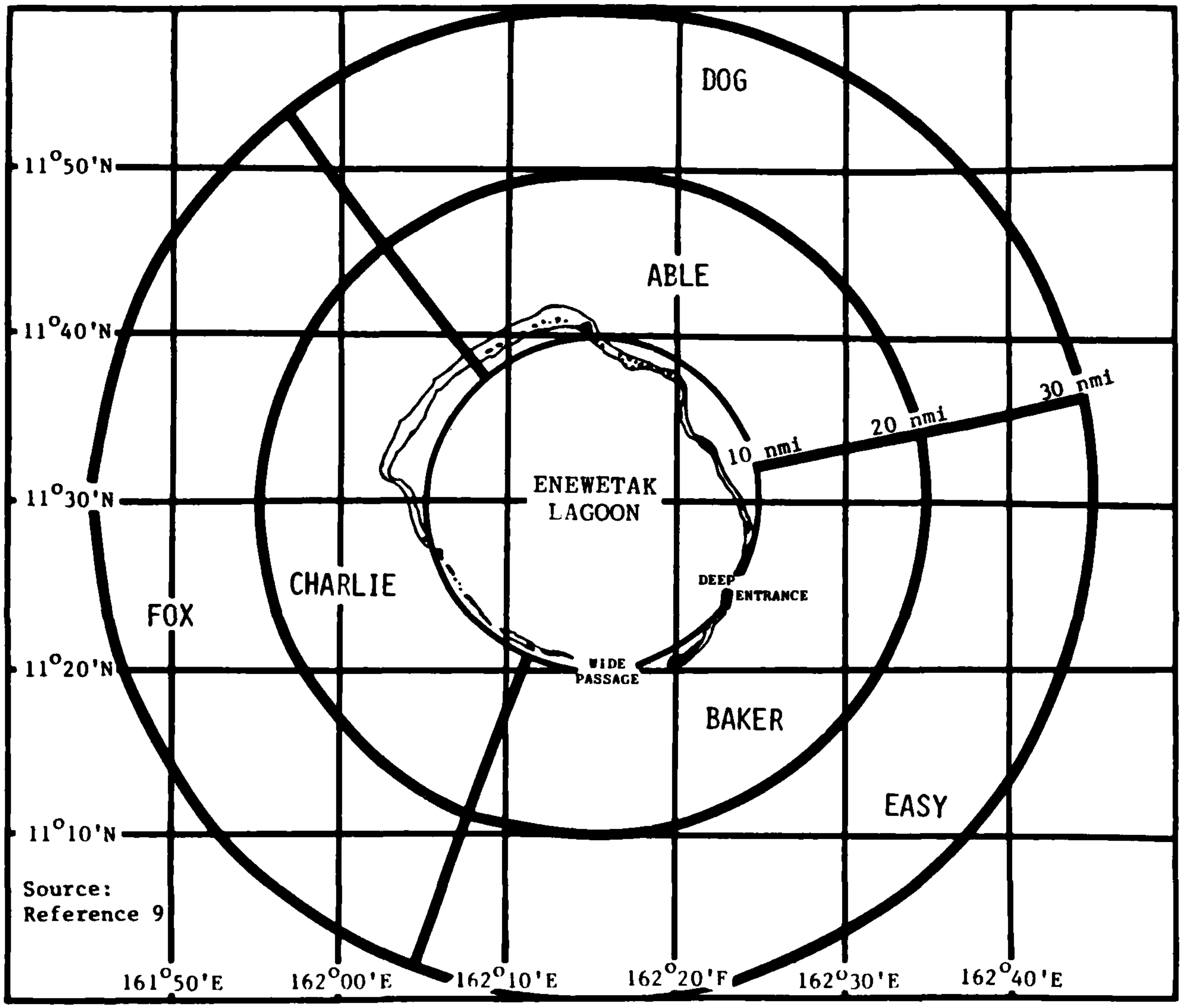


Figure 2-2. Destroyer Patrol Sector Chart for Operation SANDSTONE

Table 2-1. Destroyer Patrol Sector Assignments for Operation SANDSTONE

	PATROL SECTOR							
DATE	DEEP ENTRANCE	WIDE PASSAGE	ABLE	BAKER	CHARLIE	DOG	EASY	FOX
APRIL 15	ROG	PER	TUC/GEO	MAR	MAR	CUR	CUR	CUR
16	ROG	PER	GEO/SPA	MAR	RAB	CUR	CUR	CUR
17	ROG/MAR	PER	SPA	MAR	RAB			
18	MAR	PER/ROG	SPA	RAB	PER			
19	MAR	ROG	RAB	SPA	PER			
20	MAR	ROG	RAB	SPA	PER			
21	MAR/TUC	ROG	RAB	SPA/CUR	PER/GEO			
22	TUC/CUR	ROG	RAB	CUR	GEO			
23	TUC/RAB	ROG	CUR	CUR	GEO			
24	TUC	ROG	RAB	CUR	GEO			
25	TUC/MAR	ROG/PER	RAB	CUR	GEO/CUR			
26	MAR	PER	SPA	CUR/SPA	GEO			
27	MAR/ROG	PER	SPA/GEO	CUR/SPA	GEO/MAR	TUC	GEO/CUR	GEO/CUR
28	ROG	PER	GEO	SPA	MAR	TUC	CUR	CUR
29	ROG	PER/RAB	GEO	SPA	MAR	TUC	CUR	CUR
30	ROG	RAB/PER	GEO/TUC	SPA	MAR/SPA	TUC	CUR	CUR
May 1	ROG	PER	GEO/TUC	SPA/MAR	SPA	TUC/GEO	CUR	CUR
2	ROG/GEO	PER	TUC	MAR	SPA	GEO	CUR	CUR
3	GEO	PER/SPA	TUC	MAR/TUC	SPA		CUR/MAR	
4	GEO/SPA	SPA/MAR	TUC/GEO	RAB	TUC/GEO			
5	SPA	MAR	GEO	RAB	GEO			
6	SPA	MAR	GEO	RAB	GEO			
7	SPA	MAR/CUR	GEO/ROG	RAB	GEO/ROG			
8	SPA/PER	CUR	ROG	RAB	ROG			
9	PER	CUR	ROG/TUC	TUC	ROG			
10	PER	CUR	ROG/TUC	TUC	ROG			
11	PER	CUR	ROG/TUC	TUC	ROG			
12	PER/GEO	CUR/SPA	ROG/MAR	TUC/PER	ROG/MAR		CUR	CUR
13	GEO/ROG	SPA/PER	MAR/GEO	PER/SPA	MAR	TUC	CUR	CUR
14	ROG	PER	GEO/TUC	SPA	MAR	TUC	CUR	CUR
MAY 15	ROG/GEO	PER/CUR	TUC/GEO	MAR	MAR		CUR	

Key: CUR-CURRIER, GEO-GEORGE, MAR-MARSH, PER-PERKINS, RAB-RABY, ROG-ROGERS, SPA-SPANGLER, TUC-TUCKER

Source: Ship Deck Logs

Table 2-2. Ship Participation Summary at Operation SANDSTONE

Task Units Formed For Evacuation	Ship	Ships at Enewetak Atoll Unless Noted			Departure Date
		X-RAY	YOKE	ZEBRA	
Ships Remaining in the Lagoon	ALBEMARLE				21 May
	BAIROKO				21 May
	CURTISS				21 May
	MT McKINLEY				21 May
	SPANGLER*				21 May
TU 7.3.3	GEORGE				25 May
	PERKINS				21 May
	RABY				21 May
	ROGERS				20 May
	TUCKER				21 May
TU 7.3.5	AREQUIPA		Pearl Harbor	Pearl Harbor	20 Apr
	ASKARI				29 May
	PASIG				24 May
	LSM-250				24 May
	LSM-378	Kwajalein			24 May
	LST-45				24 May
	LCI-1054				24 May
	LCI-1090				24 May
	YOG-64				29 May
	YW-94				29 May
	AFS-211	Bikini		Mili	Unk
	AFS-370				Unk
	MARSH*				3 Jun
TU 7.3.8	COMSTOCK				31 May
	GARDINERS BAY				22 May
	MISPILLION				21 May
	PICKAWAY				27 May
	WARRICK			Kwajalein	18 May
	CURRIER*				25 May
Others Ships	LCI-549				24 May
	YANCEY	Pearl Harbor	Pearl Harbor	Arrive Enewetak 16 May 1948	26 May

*These destroyers rejoined TU 7.3.3 following each detonation. Source: Ship deck logs.

2.2 RADIOLOGICAL DATA

All three of the SANDSTONE devices were detonated on 200-foot towers over coral soil (see Table 1-1). Because the tests were detonated under nearly ideal wind conditions (which minimized fallout on the islands in the southern portion of the lagoon), none of the task group ships received any primary (early-time) fallout. Generally, as the radioactive clouds rose, the stems of the clouds would drift off to the west or northwest under the influence of the low level (≤15,000 feet) easterly or southeasterly winds; the main portion of the clouds drifted to the east or northeast under the influence of westerly or southwesterly winds above 15,000 feet (Reference 2). The clouds from each shot remained below the high Pacific tropopause; hence, the winds continued to carry them in an easterly direction. As the clouds drifted eastward and diffused, radioactive particles were continuously falling into the low-level easterly winds which would have carried some of them back toward Enewetak Atoll. This secondary (late-time) fallout appears to be the source of virtually all of the shipboard contamination on ships participating at Operation SANDSTONE. Generally, secondary fallout was a widespread phenomenon and probably occurred uniformly (with equal intensity) over Enewetak Lagoon and the waters in the immediate vicinity of the atoll. Hence, radiological data obtained aboard one ship may, in the absence of contradictory information, be applicable to other ships at or near Enewetak during the time when fallout was encountered.

Shortly after Shot X-RAY, the TUCKER and GEORGE, while operating in the area east of Enjebi Island, reportedly saw a "mist of very small particles" (from passage of the nuclear cloud), but intensities returned to normal background when the ships moved away from the visible cloud (Reference 10). The intensities apparently resulted from cloud "shine", i.e., radiation emanating from the cloud in the absence of fallout particles, since it was reported that no contamination fell on the ships. Topside intensities on the TUCKER were reported to have been 20 mR/hr ($\beta + \gamma$)* for one hour and forty minutes while beneath the radioactive cloud; intensities on the GEORGE were reported as "twice above background" for approximately fifteen minutes (Reference 10).

*Since no fallout was observed on the ships, the reported reading was probably due to gamma only; a beta contribution would suggest the presence of fallout particles.

Minor fallout did occur on Enewetak Island following the X-RAY detonation. Radiological surveys were conducted at three locations on the island during the period 15-21 April. At two of the locations, the Service Club and "Hut A", maximum intensities of 0.1 mR/hr were noted at 2100 hours, 15 April. At the same time, intensities of 0.5 mR/hr were measured in the vicinity of the TG 7.6 building (Reference 11). Another brief period of fallout occurred late in the evening of 16 April and into the morning of 17 April. Maximum intensities measured on Enewetak during this fallout were 0.1 - 0.15 mR/hr at all three locations (Reference 11); somewhat higher intensities were observed onboard the four ships anchored in the northern anchorage area of the lagoon off Enjebi and Aomon Islands (Reference 10). On 22 April, two of these ships, the ALBEMARLE and BAIROKO, reported deck intensities of 0.5 and 0.3 mR/hr, respectively. These intensities were approximately ten times higher than those being reported on the other two ships anchored in close proximity to them, the CURTISS and MT McKINLEY. Since no fallout was reported on the residence islands of the atoll during this time period, it is assumed that these greater intensities were due to contaminated helicopters landing on the flight decks of these two ships and that the readings are not representative of the weather deck surfaces on the other ships.

At 1000 hours on 3 May, two days after Shot YOKE, background intensities on the BAIROKO's flight and hangar decks "began to noticably increase, and it soon became evident that appreciable fall-out was occurring on the ship" (Reference 7). Maximum intensity readings on the BAIROKO were 1.7 mR/hr ($\beta + \gamma$) early in the afternoon, when the fallout ceased. This fallout also occurred on the other ships, but to a lesser extent than on the BAIROKO. Fallout had also occurred on Kwajalein during the evening of 2 May where average intensities were reported as 2.0 mR/hr (0.5 mR/hr gamma) (Reference 7). Maximum intensities of 6-10 mR/hr were reported in Reference 2, but these were apparently on canvas (Reference 7) and are not representative of personnel exposure.

After Shot ZEBRA there was apparently some minor fallout in Enewetak lagoon but "it decayed rapidly and never approached the tolerance limit" (Reference 7). The time that this fallout occurred and the intensity levels it reached have not been found, probably because the intensity was considered too insignificant to log.

The radiation environments on the residence islands of Enewetak and Kwajalein Atolls are depicted in Figures 2-3 and 2-4, respectively. Available shipboard data are also plotted in Figure 2-3. X-RAY, YOKE, and ZEBRA fallout on Kwajalein is well documented on two strip chart recorders that were operated by the New York Operations Office of the AEC; the strip chart traces, normalized to the survey measurement, are the sources of the intensity curve in Figure 2-4 (Reference 12). Shipboard intensity readings on the BAIROKO following Shot YOKE suggest that it received the same "wave" of fallout as that which occurred on Kwajalein approximately 12 hours earlier. Hence, the YOKE intensity curve for Enewetak (Figure 2-3) is obtained from the peak reading on the BAIROKO with subsequent decay dictated by the Kwajalein data. Since no intensity data are available for fallout on Enewetak following Shot ZEBRA, the high-sided assumption is made that it received another minor "wave" of fallout with intensities comparable to those on Kwajalein.

On 18 May, three days after Shot ZEBRA, all of the task group ships in the lagoon were inspected by monitoring parties. Particular attention was paid to the blower intake screens, the open decks, the evaporators, the auxiliary condensers, and any cargo onboard the ship (Reference 7). The crews were directed to decontaminate any areas with intensities greater than 5 mR/day ($\beta + \gamma$) above background. The ships were reinspected on 20 May. Final radiological clearance was given to all ships reporting maximum intensities of less than 5 mR/day, and an operational clearance was given to those ships where isolated intensities in excess of this were still being reported. For those ships departing Enewetak under an operational clearance, it was directed that the inlet screens to supply blowers be scraped to bare metal, repainted and monitored on arrival at a shipyard. It was reported that there was "no radioactive hazard to personnel on any ship" as of 20 May 1948 (Reference 7). The results of the 20 May survey are contained in Reference 13; the average gamma intensity on the weather surfaces of all ships is also plotted in Figure 2-3. It should be noted in the 20 May survey data that the vast majority of the shipboard intensity measurements were obtained from locations such as air intakes, engine room blowers, vent duct screens, and exhaust vents. These locations would be expected to accumulate any radioactivity and therefore the readings represent the maximum shipboard intensities at the time of the survey. Weather deck intensities, when reported, are generally lower and are more representative of average topside intensities.

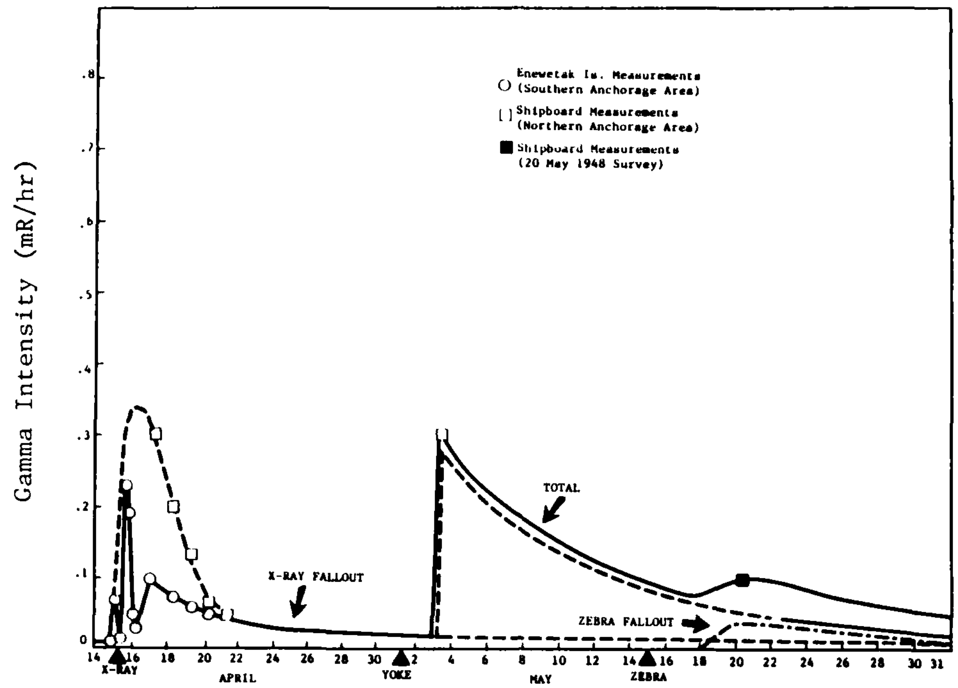


Figure 2-3. Average Free-Field Radiation Intensity for Southern and Northern Anchorage Areas - Enewetak Atoll

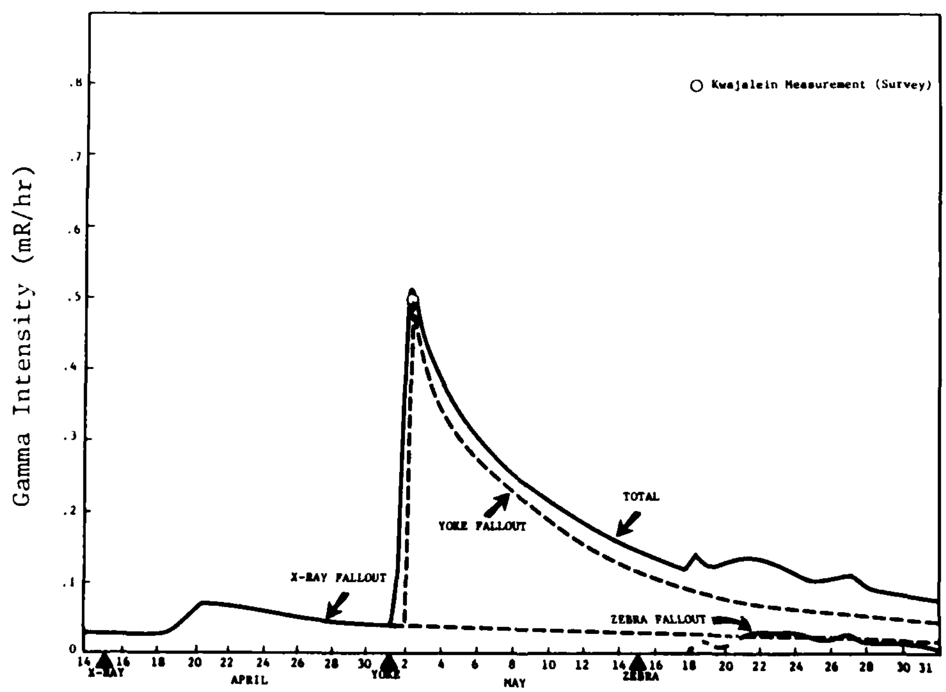


Figure 2-4. Average Free-Field Radiation Intensity on Kwajalein

2.3 INTEGRATED FREE-FIELD INTENSITIES

The intensity curves derived in Section 2.2 are time-integrated to arrive at the free-field radiation environment on Enewetak and Kwajalein Atolls, and on those ships where sufficient radiological data exist to derive their intensity curves. For those ships remaining in the southern anchorage area at Enewetak, the free-field radiation environment on Enewetak Island is considered to be the topside environment. For those ships at Kwajalein at the time of fallout, the Kwajalein environment is considered to be the topside environment. Ships that were not at Enewetak or Kwajalein in the days immediately following a given shot are assumed to have not received fallout from that test (no existing data suggets otherwise). Calculations are carried out to 31 May, at which time the daily free-field integrated intensity increment is approximately 1 mR. Subsequent decay would have soon rendered the daily increment comparable to normal background.

The basic expression used to calculate the integrated free-field intensity is given by:

$$\int_{t_1}^{t} I(t)_{X\text{-}RAY}\,dt + \int_{t_2}^{t} I(t)_{YOKE}\,dt + \int_{t_3}^{t} I(t)_{ZEBRA}\,dt$$

where

t_1, t_2 and t_3	=	Fallout arrival times for Shots X-RAY, YOKE, and ZEBRA, respectively, in hours after the shot.
$I(t)$	=	Intensity (mR/hr) with respect to time after Shots X-RAY, YOKE, and ZEBRA.

The upper limit of integration, t, is the end of the period for which it is desired to calculate the environment, 31 May 1948. The results are given in Table 2-3.

Table 2-3. Integrated Free-Field Intensities Through 31 May 1948

Location	Integrated Intensity (mR)
Atolls	
Enewetak	101
Kwajalein	151
Ships	
ALBEMARLE, BAIROKO, CURTISS, GEORGE, LST-45, MT McKINLEY	117
AFS-211	75
AREQUIPA	26
LSM-378	114
TUCKER	150
WARRICK	93
YANCEY	8
All other ships: AFS-370, ASKARI, COMSTOCK, CURRIER, GARDINERS BAY, LCI-549, LCI-1054, LCI-1090, LSM-250, MARSH, MISPILLION, PASIG, PERKINS, PICKAWAY, RABY, ROGERS, SPANGLER, YOG-64, YW-94	101

2.4 SHIP SHIELDING

Dose estimates for crewmembers require consideration of the shielding provided by the ship structure for radioactive fallout deposited on the weather surfaces of the ships. A ship-shielding factor, defined as the ratio of radiation intensity at an interior location to an intensity topside, depends on many variables: time after detonation, distribution of fallout on the weather surface, amount of intervening material (decking, bulkheads, piping, etc.) from weather surface to point of interest, and distance from weather surface. Consequently, while ship shielding effects have been experimentally and theoretically studied by the Navy since Operation CROSSROADS (1946), values of shielding factors remain uncertain. Readings taken on target ships

during Operation CROSSROADS, and on two test ships (YAG-39 and YAG-40) during Operations CASTLE (1954) and REDWING (1956) gave preliminary estimates of shielding factors (References 14, 15 and 16). However, a significant fraction of the radiation penetrating to the interior of these ships, especially at the lower depths, apparently came from radioactive materials in the water and on the hulls of the ships. Because this radiation source is insignificant in the extant case, these shielding factors are not applicable.

Experimental results reported by W.F. Waldorf (Reference 17) on radiation from Cobalt-60 and Cesium-137 sources on the flight deck penetrating the interior of a light aircraft carrier (USS COWPENS) indicated that an average shielding factor could be correlated with the thickness of deck plating directly above the point of interest in the ship. He further showed that the effects of bulkheads, piping, and other miscellaneous intervening material could be approximated (somewhat high-sided) by doubling the deck thickness in shielding calculations. Results from British experiments on a carrier, destroyer, and light cruiser, referenced by Waldorf, verified these conclusions and indicated that this factor of two may apply to most ship types. C.F. Ksanda (References 14 and 18) performed detailed calculations on an aircraft carrier (USS RANGER), presenting the shielding factors graphically as functions of deck plating thickness for various times after detonation. He also accounted for miscellaneous shielding materials by doubling the deck thickness when performing the calculations. The results of the Waldorf experiment and the geometric means of Ksanda's upper and lower limit shielding factors for unfractionated U-235 fission products at one day after detonation are displayed in Figure 2-5. Due to geometric attenuation, these curves appear to approach values less than one as deck thickness becomes small. Because of the detailed nature of Ksanda's effort and the general agreement with experiment, the Ksanda mean value is used in the present calculations.

In the present analysis, it is assumed that, when topside, personnel experienced the average external topside intensity, and any shielding provided by the superstructure is neglected. Large variations in personnel activities and shielding factors preclude a more accurate assessment of this factor. It is further assumed that, when below decks, personnel were located on the second deck, with only the thickness of the

main deck to provide radiation shielding. Personnel below the second deck, and in those portions of the second deck under the superstructure, were afforded additional radiation shielding not included in these calculations. The main deck thicknesses for the types of ships at Operation SANDSTONE are estimated to range between 0.30 and 0.75 inches (Reference 5 and 6). From Figure 2-5 this would correspond to a range in shielding factors of 0.15 to 0.06, respectively.

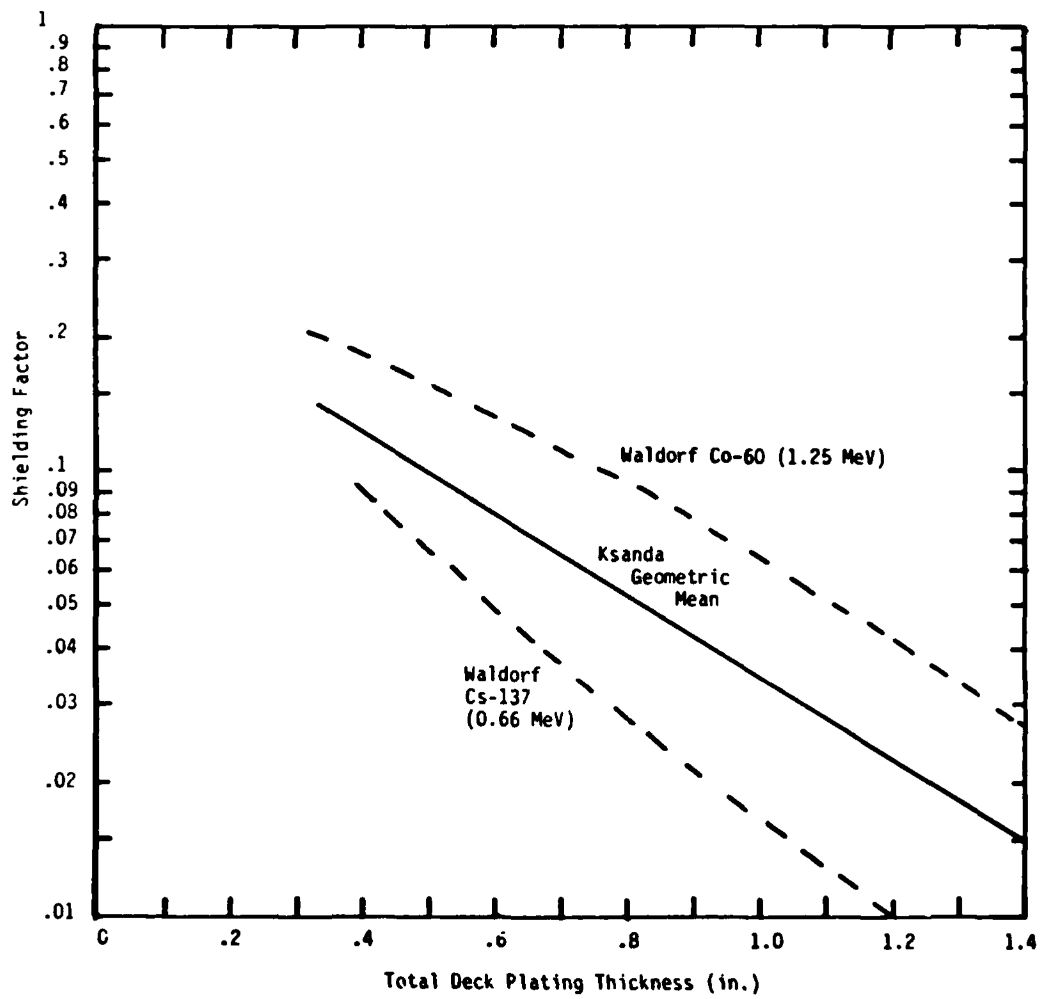


Figure 2-5. Ship Shielding Factor vs. Deck Plating Thickness

Section 3

DOSE CALCULATIONS

To determine the dose to personnel, consideration is given to the time spent topside (outside) and below decks (inside) and the radiation protection afforded by a ship (building). The free-field integrated intensities from Section 2 are adjusted to account for crew activities, either documented or assumed. The adjusted exposures (mR) are then multiplied by a film badge conversion factor to determine a film badge dose. This conversion factor, derived in Reference 8, is approximately 0.7 mrem/mR. Results are presented as a cumulative dose to personnel through 31 May 1948.

The average free-field integrated intensity is converted to a film badge dose and corrected to account for the shielding provided by the ship's structure while personnel were below decks. Similar protection is afforded by buildings in the case of the island-based personnel. Normally, during fallout deposition and at early times when intensities are relatively high, an estimate of personnel protective measures is critical in determining the film badge dose (References 5 and 6). At Operation SANDSTONE, however, all fallout was relatively minor, and normal crew routines were probably not significantly altered during periods of fallout deposition. To determine film badge doses, the time-integrated intensities are adjusted to account for the time spent topside (outside) and below (inside) during a typical work day. It is estimated that the typical crew on each ship was on deck at the following times: 0800-1200, 1330-1730, and 1800-2000 hours. This amounts to 40 percent of the day (9½ hours) topside and 60 percent (14½ hours) below. While below, the crew was afforded shielding provided by the ship's structure. In Section 2.4 it is estimated that the ship-dependent shielding factors vary from approximately 0.06 to 0.15, depending on the main deck thickness. A time-averaged shielding factor is computed as 0.4 + 0.6 x ship-shielding factor, where the 0.4 and 0.6 represent the fraction of the day spent above and below deck, respectively. The time-averaged shielding factors vary from 0.44 to 0.49. An average value of 0.47 is used in the analysis and variations in this value are treated as an uncertainty in Section 4. A similar argument is used to obtain a time-averaged shielding factor of 0.8 for the land-based personnel. This assumes that 60 percent of

the day is spent outside and 40 percent inside. While inside, personnel are afforded a protection factor of 2, i.e., a shielding factor of 0.5.

The integrated intensities in Table 2-3 are corrected to account for shielding provided by a ship's structure and buildings on the residence islands, and film badge equivalency. Results are personnel film badge doses through 31 May and are given in Table 3-1.

Table 3-1. Calculated Personnel Film Badge Doses Through 31 May 1948

Location	Film Badge Dose (mrem)
Island Based Personnel	
Enewetak Atoll	57
Kwajalein Atoll	84
Shipboard Personnel	
ALBEMARLE, BAIROKO, CURTISS, GEORGE, LST-45, MT McKINLEY,	39
AFS-211	25
AREQUIPA	9
LSM-378	37
TUCKER	49
WARRICK	31
YANCEY	3
All other ships: AFS-370, ASKARI, COMSTOCK, CURRIER, GARDINERS BAY, LCI-549, LCI-1054, LCI-1090, LSM-250, MARSH, MISPILLION, PASIG, PERKINS, PICKAWAY, RABY, ROGERS, SPANGLER, YOG-64, YW-94	33

Section 4

UNCERTAINTY ANALYSIS

The uncertainty in calculated film badge dose is estimated from the underlying parameters. The basic uncertainties include radiation intensities on shipdeck or on islands, the time spent on deck or outside, and the shielding afforded to personnel below decks or within buildings.

Intensity levels on deck are determined from limited shipboard radiological survey data, supplemented by the more continuous island readings from Enewetak and Kwajalein Atolls. The sparsity of the data requires a high-sided approach to the assignment of time-dependent ship intensity levels. However, the high-siding does not extend to the uncritical incorporation of all maximum readings. Where readings are demonstrably unrepresentative of a topside intensity, whether from documented hotspots or as deduced from neighboring ship data, they are excluded. The ALBEMARLE and BAIROKO readings of 22 April (D+7) are thus excluded, as are the 20 May survey readings of air intakes and the like.

The most complete and reliable intensity data are those derived from daily counting on Kwajalein Atoll. In the weeks following Shots X-RAY and YOKE, the activity decays as approximately $t^{-1.1}$ (minus background). For the periods of interest, Reference 19 indicates a nearly constant ratio between activity and gamma intensity. With the reported peak gamma reading after YOKE for normalization, the gamma intensity is thus implied throughout. The $t^{-1.1}$ decay is taken as appropriate for Enewetak Atoll as well and leads to high-sided doses when applied to early shipboard readings (because of deck weathering). Two independent types of counting are available from Kwajalein. The corresponding plots are very similar (up to an unknown constant) except near the peak after YOKE. Consequently, the normalization of each to gamma intensity is different. The normalization chosen for dose computation is that from the depressed peak, thereby implying greater intensities at other times by more than a factor of two. Thus, the total dose calculated for Kwajalein personnel may be high-sided by about a factor of two.

Enewetak Island intensity data, as extrapolated by $t^{-1.1}$ decay, are also applied after Shot X-RAY to ships in the adjacent southern anchorage, for which no data are available. The resulting doses are considered to be high-sided for shipboard personnel, as the island data also decay by $t^{-1.1}$ after the cessation of fallout. Readings are available for three locations on Enewetak Island, several times daily, until four days after X-RAY. Peak readings range as high as twice the mean intensities used in dose computation and may be considered as leading to a reasonable upper limit of dose.

For ships in the northern anchorage after Shot X-RAY, intensity data are available from four ships for D+4 to D+7. These deck data are consistent to within about 50 percent of their mean, with the exception of the D+7 data noted previously. The only earlier data are beta/gamma readings on D+2 and D+3 from the BAIROKO. These, together with the timing of the fallout deposition on D+1 from the island data, permit reconstruction of the time-dependent intensity aboard the ships. The ratio of beta/gamma to gamma needed for the computation is obtained from analysis of the fifty available shipboard measurements of both quantities after Shots X-RAY and ZEBRA (References 10 and 13). These ratios form a lognormal distribution with 90 percent of the data within a factor of two of the geometric mean. Thus, the two BAIROKO readings, even if representing a systematic bias in measuring technique, should imply a gamma intensity good to within a factor of two with 90-percent confidence. An additional uncertainty is with regard to the magnitude of the peak intensity on D+1. A high-sided dose is obtained by assuming a rapid deposition such that radiological decay alone accounts for the decline in intensity from D+1 to D+2. A more realistic dose follows from a flatter peak that represents an interval(s) of fallout deposition, as suggested by the island data. However, the shape of the D+1 peak affects the total dose from Shot X-RAY by less than 10 percent.

The only datum at Enewetak Atoll after Shot YOKE is the peak beta/gamma reading onboard the BAIROKO. That reading, the maximum among the ships (Reference 7) is taken as a high-sided value for all ships and Enewetak Island. With $t^{-1.1}$ decay as on Kwajalein Atoll (minus the background from Shot X-RAY), shipboard doses are additionally high-sided. The uncertainty in the ratio of beta/gamma to gamma readings implies a peak gamma intensity (and therefore the high-sided dose from YOKE fallout) good to within a factor of two with 90-percent confidence.

No data specific to Shot ZEBRA are available for Enewetak Atoll. Intensities were apparently too low to warrant recording; the contribution to dose must have been very small, as on Kwajalein Atoll. What data are available, from ship surveys on 20 May, likely reflect a dominant contribution from Shot YOKE. Of those readings representative of topside contamination, 60 percent of the mean intensity is accounted for by $t^{-1.1}$ decay of the YOKE fallout on the BAIROKO (including a small contribution from X-RAY). The remaining intensity is attributed to Shot ZEBRA and implies a dose similar to that on Kwajalein Atoll, or about 10 percent as much as the dose contribution from Shot YOKE. In the limit of rapid decay of the YOKE fallout, such that the surveys represent almost entirely ZEBRA fallout, the dose from Shot ZEBRA could be as great as twice that calculated. However, for ships other than the YANCEY, the consequent reduction in the YOKE dose more than offsets this increase. In fact, for the upper-limit contribution from YOKE, the ZEBRA contribution that can be accommodated is negligible. The only manner in which the ZEBRA contribution could be increased independently is through the uncertainty in the mean survey reading. The sixteen readings considered to be representative of topside conditions ensure that the uncertainty in this mean is low; it is accurate to within 20 percent with 90-percent confidence. Consequently, the ZEBRA dose is not more than a factor of $(.4+.2)/.4=1.5$ too low from this source with at least 90-percent confidence; in the limit of negligible YOKE contribution it is $(2x.4+.2)/.4 = 2.5$ too low.

The above uncertainties in free-field intensities dominate the uncertainties in personnel dose calculations. Having less influence are the time-averaged shielding factors for shipboard and land exposures. The value of the fraction of time spent on deck or outside is estimated to be accurate within a factor of 1.2 with 90-percent confidence. Shielding factors below decks and in buildings are estimated to be accurate within a factor of 1.5. Overall, the time-averaged ship factor is $0.47^{+0.10}_{-0.08}$ and the land factor 0.80 ± 0.13 to greater than 90-percent confidence.

Combined, upper-limiting uncertainties are summarized in Table 4-1 in terms of error factors to at least the 95-percent level (viz., upper 90-percent limit) for each discrete exposure analysis, where not already high-sided.

Table 4-1. Upper Bound Error Factors for Ships and Islands

Location	Shot	Error Factor
Enewetak Island	X-RAY, YOKE	2.5
Southern Anchorage	X-RAY, YOKE	2.4
Northern Anchorage	X-RAY: 15-18 Apr	2.4
	After 19 Apr	1.8
	YOKE	2.4
USS YANCEY	ZEBRA	3.0
Kwajalein Atoll	All	1.2

These error factors are applied to the average personnel film badge doses calculated in Section 3 (Table 3-1). The results of the best-estimate and upper bound dose calculations are summarized in Section 6.

Section 5

FILM BADGE DOSIMETRY

In order to assess the validity of the dose calculations presented in Section 3, the Reynolds Electrical and Engineering Company's (REECo) exposure records for Operation SANDSTONE (Reference 20) were reviewed. Of the many personnel film badge exposure records maintained on file, approximately 100 were identified as being representative of "typical" personnel exposures on the ships and islands of interest. In this section, the actual dosimetry records for SANDSTONE personnel are compared to the calculated average film badge dose. The periods of badged exposure vary from ship to ship; therefore, dose calculations are performed for these specific badged periods in order to provide a basis for comparison.

Generally, film badges were issued to personnel aboard the ships in order to obtain a record of exposure in various parts of the ship at the time of, and subsequent to, the detonation. These badges were usually issued several days prior to each test. These "shot" badges form the basis for the comparison with calculations. Other badges were issued to personnel during the periods between shots when they were expected to enter, or be in the vicinity of, radioactive areas. These are referred to as "mission" badges and represent non-typical exposures; hence, they are not included in the comparison. The majority of the badges issued for Operation SANDSTONE appear to fall into this category. These badges were issued to rad-safe personnel, members of the boat pool, and others who were required to be in contaminated areas.

Table 5-1 summarizes, by shot, the dosimetry data selected for the comparison and the corresponding calculated film badge dose. Also tabulated are the number of "shot" badges identified as being issued for each shot on each ship (atoll), where available. The average film badge dose (FB) is simply the arithmetic mean of the doses derived from the exposed badges; the calculated dose (Calc) covers the corresponding badge period.

Table 5-1. Comparison of Dosimetry with Calculated Film Badge Doses

	XRAY			YOKE			ZEBRA		
	Number of Badges	Dose (mrem) FB	Dose (mrem) Calc	Number of Badges	Dose (mrem) FB	Dose (mrem) Calc	Number of Badges	Dose (mrem) FB	Dose (mrem) Calc
BAIROKO	(3)	2	3	(7)	3	2	(10)	31	2
COMSTOCK	(7)	1	3	(7)	0	3	(10)	12	3
TUCKER	(20)	19	14	(1)	0	7	--	--	--
ALBEMARLE	(2)	0	4	(1)	0	1	(3)	3	4
MT MCKINLEY	--	--	--	(5)	0	1	(3)	2	3
PICKAWAY	(4)	26	1	(5)	30	1	--	--	--
SPANGLER	--	--	--	(1)	5	9	--	--	--
GEORGE	--	--	--	(1)	0	1	--	--	--
ENEWETAK	(3)	0	2	(6)	0	3	(6)	3	4
KWAJALEIN	--	--	--	--	--	--	(3)	10	9

With the exception of the BAIROKO (Shot ZEBRA) and the PICKAWAY (Shots X-RAY and YOKE), calculated doses are consistent with the actual film badge data. It should be noted, however, that the maximum dose recorded by any of the "shot" badges (with the exception of those onboard the BAIROKO and PICKAWAY) was 40 mrem, which was below the film badge sensitivity threshold of approximately 50 mrem. Therefore, the only reasonable statement that can be made concerning the dose calculations are that the low calculated doses are substantiated by the low film badge exposures for the majority of the ships.

On the BAIROKO, ten film badges have been identified as being "shot" badges issued for Shot ZEBRA. The ten readings are as follows: 25, 40, 36, 35, 20, 40, 60, 50, 0, and 0 mrem. The first five badges have been further identified as being issued to either rad-safe officers or members of the boat pool, leaving only five badges as being issued to "typical" crewmembers. Of these five, two are zeros and the average of the remaining three is 50 mrem. Shipboard radiological data obtained during the 20 May survey, extrapolated back to 14-15 May when the badges were worn, do not support the atypical 40-60 mrem doses.

Four film badges were issued to personnel onboard the PICKAWAY for Shot X-RAY. These badges recorded exposures of 0, 35, 20, and 50 mrem. The zero dose was assigned to a crewmember identified as being a rad-safe officer who would have been involved with shipboard radiological surveys. The remaining three badges were issued to the Commanding Officer (35 mrem), the Executive Officer (20 mrem) and the Damage Control Officer (50 mrem)---certainly not typical crewmembers.

For Shot YOKE, five badges were issued to personnel aboard the PICKAWAY. Two of the badges were issued to a rad-safe officer and recorded doses of 0 and 40 mrem. These readings, obtained on the same individual during the same period of time, support the premise that readings below the film badge sensitivity threshold of approximately 50 mrem are unreliable. The remaining three badges were again issued to non-typical crewmembers: the Commanding Officer (40 mrem), the Executive Officer (40 mrem), and the Navigator/Operations Officer (30 mrem).

All of the badges issued to personnel on the PICKAWAY are at, or below, the film badge sensitivity threshold. Available radiological data do not support the recorded exposures for Shots X-RAY and YOKE. In fact, YOKE fallout, the major contribution to the shipboard dose, did not occur until 3 May--two days after the YOKE badges were turned in. Fourteen film badges exposed onboard the COMSTOCK which was anchored just 500 yards from the PICKAWAY following Shots X-RAY and YOKE, recorded exposures of zero mrem (13 badges) and 10 mrem (1 badge).

Section 6

CONCLUSIONS AND TOTAL DOSE SUMMARY

Of the three shots of Operation SANDSTONE, Shots X-RAY and YOKE contributed over ninety percent of the gamma radiation dose to personnel on the participating ships and on the islands of Enewetak and Kwajalein Atolls; Shot ZEBRA contributed the remainder. Personnel on ships that returned to the northern anchorage area of Enewetak Atoll following each of the three shots received slightly greater doses than personnel on ships that remained in the southern anchorage area. Shipboard personnel, in general, received smaller doses than the island-based personnel due to effective shielding provided by the ship's structure when personnel were below decks. The crews of the thirty-one vessels participating at SANDSTONE received doses of 0.05 rem or less. Personnel on Enewetak and Kwajalein Atolls received doses of approximately 0.06 and 0.08 rem, respectively.

Because of uncertainties associated with both shipboard and island radiological data, as well as those associated with the actual time spent on deck and ship shielding provided while below deck, calculations could be approximately twice the best estimate calculated in Section 3. This implies an upper-bound dose of less than 0.10 rem for shipboard personnel. Similar considerations for island-based personnel lead to upper-bound doses on Enewetak and Kwajalein of approximately 0.13 and 0.10 rem, respectively. Calculated doses are summarized in Table 6-1.

Available film badge dosimetry supports the reconstructed doses for TG 7.3 personnel at Enewetak and Kwajalein Atolls during Operation SANDSTONE. Virtually all of the actual exposure records obtained from shot badges are below the film badge threshold of approximately 0.05 rem. Calculated doses for periods of time corresponding to the badged periods are consistent with these "below threshold" exposures. Film badge doses onboard two ships, the BAIROKO and PICKAWAY, indicate higher exposures than the reconstructed doses would suggest. This inconsistency may be attributed to the fact that the film badge records on these ships represent non-typical exposures, since available shipboard radiological data do not support the recorded doses.

Table 6-1. Summary of Calculated Doses

Location	Best-Estimate Dose* (rem)	Upper Bound Dose* (rem)
Island Based Personnel		
Enewetak Atoll	0.06	0.13
Kwajalein Atoll	0.08	0.10
Shipboard Personnel		
ALBEMARLE, BAIROKO, CURTISS MT McKINLEY, LST-45, GEORGE	0.04	0.08
AFS-211	0.03	0.06
AREQUIPA	0.01	0.02
LSM-378	0.04	0.07
TUCKER	0.05	0.09
WARRICK	0.03	0.07
YANCEY	0.01	0.01
All other Ships: AFS-370, ASKARI, COMSTOCK, CURRIER, GARDINERS BAY, LCI-549, LCI-1054, LCI-1090, LSM-250, MARSH, MISPILLION, PASIG, PERKINS, PICKAWAY, RABY, ROGERS, SPANGLER, YOG-64, YW-94	0.03	0.07

*Doses are rounded to the nearest 0.01 rem.

Section 7

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